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We consider two recently accentuated, unusual empirical results concerning cosmic-ray events at high energies. We show that the possibility for a correlated explanation is provided by new dynamics which arises from collisions of a neutral Goldstone boson as a component of the highest-energy cosmic rays.

In this paper, we consider the hypothesis that there is a nearly-massless neutral Goldstone boson, b^0, which is a component of high-energy cosmic rays and which is initiating air showers [1–3] at the highest energies and possibly also anomalous multiple-core structure seen in photo-emulsion chamber experiments [4–8]. We point out and examine the consequences of new dynamics which arises from the assumption that there is an effective interaction originating in a neutral triangle anomaly [9,10] involving b^0 and a neutral vector boson Z' (and/or a chirally-related neutral axial vector boson). This possibility may be related to the possibility that neutrino mass originates as a consequence of a spontaneously broken chiral symmetry at a low energy scale, $F \sim 0.4$ MeV. The strength of the effective interaction is $(\frac{g^2}{2\pi^2 F})$ with g^2 assumed, for numerical illustration of the idea, to be of the order of 0.1 (i. e. like a strength for Z). [11] The communication of b^0 with quarks is only via Z' exchange; among leptons, Z' likely couples only to neutrinos (like b^0).Then the mass of Z' may not be very much greater than that of Z. An actual value up to some hundreds of GeV does not affect our display of interesting dynamics, because we are considering cosmic-ray collisions at (c. m.) energies well above $m_{Z'}$, i. e. >10 TeV for b^0-nucleon collisions (>1 TeV for an idealized b^0-quark collision).

Our main purpose is to clearly exhibit the relevance of the hypothesis to providing new dynamics bearing upon two long-standing puzzling aspects of cosmic-ray interactions at the highest energies. 1. The presence of a few "hadron-like" air shower events at primary energies estimated to be about 10^{20} eV. [1,2] The data still is limited, but this is an energy above the Greisen-Zatsepin-Kuzmin cut-off [12,13] for arrival of protons from sources at very great (cosmological) distances, because of their interaction with the cosmic microwave background photons. These events could be related to neutral b^0 arriving from even the largest distances and interacting rather strongly in the atmosphere, if a sufficient flux of b^0 at $\sim 10^{20}$ eV is attainable. We estimate below that a flux of $\sim 10^{-20}(\text{ cm}^2 - \text{ s} - \text{ sr})^{-1}$ is attainable for b^0 originating in the decay of massive inflatons which we have shown [14] can constitute much of dark-matter, and for which we have calculated [14] a lifetime orders of magnitude greater than the present age of the universe. 2. Over many years, a number of unusual events of a particular kind [6,7] at high energies have been observed in several photo-emulsion chamber experiments at different high-altitude locations [7]. These events at $E_{\text{lab}} \sim 10^{16} - 10^{17}$ eV involve double-core γ-families, where a γ-family consists of a bundle of high-energy particles incident on the chamber in almost the same direction. In the laboratory, the direction is in the very forward region for the collisions. Recently [6–8], these events have been analyzed in terms of high transverse momentum jet production in QCD. The result of this analysis [6–8], which must be viewed in the context of limited statistics, is stated to be an order of magnitude excess of events at the largest inferred [8] transverse momenta. It is said to be suggestive of new physics above $\sim 10^{16}$ eV characterized by particle production in the forward direction with unusually large transverse momenta. [8,15] In fact, an early summary of cosmic rays [4] already presented a number of events involving "binocular" families, analysis of which indicated an unusual general characteristic of forward production at transverse momenta of some tens of GeV of a decaying entity with an effective mass of tens of GeV. Subsequent data [5] indicated family events at energies above 10^{16} eV characterized by large production transverse momenta, and a rich hadron content. We show below that the cross section for production of Z' by b^0 must be dynamically enhanced at the largest values of the squared four-momentum transfer to a nuclear target. There is a large deep-inelastic cross section. Decay of Z' into quark and antiquark and quark ejection from the target (followed by fragmentation and secondary hadronic interactions) naturally gives rise to events having two cores with large transverse momenta in forward directions (and also possibly to three such cores [4]).

To clearly see the dynamical features, consider production of Z' in a b^0-quark collision via exchange of Z', as in the diagram in Fig. 1a. The interaction at the upper vertex is $(\frac{g^2}{2\pi^2 F})(\frac{1}{4}\epsilon_{\mu\nu\sigma\rho}F^{\mu\nu}_{Z'}F^{\sigma\rho}_{Z'})$; at the lower vertex $g(\overline{\psi}_q\gamma^\mu\psi_q Z'_\mu)$. The differential cross section is then

$$\frac{d\sigma}{d(\cos\theta)} \cong \left(\frac{g^2}{2\pi}\right)\left(\frac{g^2}{2\pi^2 F}\right)^2 \frac{\frac{s^2}{4}\left(\sin^2\theta + \frac{1}{4}(1-\cos\theta)^3\right)}{\left(\frac{s}{2}(1-\cos\theta) + m^2_{Z'}\right)^2} \tag{1}$$

The mass $m_{Z'}$ (taken as $\sim m_Z$ simply for numerical illustration) is retained only in the propagator (to avoid singular behavior in the squared four-momentum transfer $-t = \frac{s}{2}(1-\cos\theta))$. For c. m. energy $\sqrt{s} \sim 1$ TeV ($E^b_{\rm lab} \sim 10^{17}$ eV on $m_q \sim 5$ MeV), the total cross section is large, ~ 10 mb. This is the first feature, which is due to the low scale F. The second feature is the marked enhancement at the largest $|t|$, which is caused by the numerator function in Eq. (1). [16] Most of σ arises from $|t| \geq m^2_{Z'}$. These two features carry over to the realistic situation involving deep-inelastic interactions of b^0 impinging upon nucleons in the atmosphere, as in the diagram in Fig. 1b. In terms of the usual parton model variables $x = \frac{|t|}{2m_N(E_b - E_{Z'})}$, $y = \frac{(E_b - E_{Z'})}{E_b}$, and the nucleon structure function $F_2(x,|t|)$, the laboratory differential cross section is

$$\frac{d^2\sigma_b}{dxdy} = \left(\frac{g^2}{4\pi}\right)\left(\frac{g^2}{2\pi^2 F}\right)^2 \frac{\frac{s}{8}|t|}{(|t| + m^2_{Z'})^2}\frac{F_2}{2}\left(1 + (1-y)^2 + \frac{y^2}{2}\right) \tag{2}$$

with $s \cong 2m_N p_b$, $|t| \cong 4p_b p_{Z'} \sin^2\frac{\theta}{2}$. We have retained $m_{Z'}$ only in the propagator, m_N is the nucleon mass, p_b, $p_{Z'}$ are momenta, and θ is the angle of Z'. The total cross section is of the order of 10^{-2} mb. This is a large deep-inelastic cross section, because it is controlled by $\left(\frac{1}{2\pi^2 F}\right)^2$. Compare Eq. (2) to the usual cross section for deep-inelastic scattering of a charged lepton via photon exchange, whose size is controlled by $\sim \frac{1}{|t|}$

$$\frac{d^2\sigma_\ell}{dxdy} = \frac{(e^2)^2}{4\pi}\frac{s}{(|t|^2)^2}\frac{F_2}{2}\left(1 + (1-y)^2\right) \tag{3}$$

In this comparison, one sees again the enhancement at the largest $|t|$ due to the numerator in Eq. (2). The double-core events do indicate a fall off consistent with $(\frac{1}{p_T^2})$, not $(\frac{1}{p_T^4})$, at the largest inferred [8] transverse momenta p_T. The two features are just what is required to deal with the two unusual empirical aspects of the high-energy cosmic-ray interactions, if sufficient flux of b^0 here is achievable.

Consider first b^0 near to the maximum energy, which we consider to be $\sim 10^{20}$ eV. The maximum energy of b^0 arises from their possible origin in the decay of inflatons ϕ, $\phi \to bb$. We have calculated the ϕ mass in detail [14] in a specific phenomenological cosmological model. It is in a limited range $\sim 10^{19}\!- \sim 10^{20}$ eV. The mass range is based upon explicit calculation of inflaton potentials which exhibit <u>both</u> a minimum at an energy scale $\phi_c \cong 10^{16} - 10^{17}$ GeV and a maximum at the Planck scale. [14,17] We have shown that the massive inflaton quanta produced near the end of inflation can constitute much of dark matter today, with an energy density estimated to be in the range $0.1 - 0.5$ of critical. The inflaton may not be completely stable. In the model [14], it has no coupling to ordinary matter except for a possible very weak coupling to neutrinos proportional to neutrino mass; this leads to the decay $\phi \to \nu_\tau \overline{\nu}_\tau$ with a lifetime given by [18]

$$\tau_\phi = (\Gamma_\phi)^{-1} \sim \left((10^{-5})\left(\frac{m_{\nu_\tau}}{\phi_c}\right)^2 \frac{m_\phi}{8\pi}\right)^{-1} \cong 10^{26}\ \mathrm{s} \tag{4}$$

where we use here $m_{\nu_\tau} \cong 0.06$ eV as a hypothetical heaviest-neutrino mass, and our calculated [14] values $\phi_c \cong 10^{17}$ GeV, $m_\phi \cong 5 \times 10^{10}$ GeV. A possible "mixing" between the chiral-like dynamics [19] which we examined in the cosmological model [14], and a possible low-scale chiral dynamics involved in neutrino mass suggests an effective interaction $f(\phi bb)$, with the order of magnitude of f given by [20]

$$f \sim \left(\sqrt{10^{-5}} m_{\nu_\tau}\right)\left(\frac{m_{\nu_\tau}}{4\pi^2 F}\right) \tag{5}$$

This results in a definite branching ratio, $(\Gamma(\phi \to bb)/\Gamma(\phi \to \nu_\tau\overline{\nu}_\tau)) = r \sim 0.5 \times 10^{-4}$. We have estimated [21,22,14] that the decay of dark matter can give rise to significant flux of the maximum-energy neutrinos here, about $2 \times 10^{-16}(\mathrm{cm}^2 - \mathrm{s} - \mathrm{sr})^{-1}$ from within our galaxy alone. The estimate for r thus implies a flux of b^0 of $\sim 10^{-20}(\mathrm{cm}^2 - \mathrm{s} - \mathrm{sr})^{-1}$. In fact, the recent AGASA data [1] consists of a handful of "hadron-like" events, all close to 10^{20} eV, in an exposure of about $2.6 \times 10^{20}(\mathrm{cm}^2 - \mathrm{s} - \mathrm{sr})$. We have given numerical examples of a possible "bump" structure [22] in events near to the maximum energy, that is a structure above the GZK cut-off and near to 10^{20} eV.

The anomalous double-core events [8] imply a flux of b^0 of the order of $10^{-16}(\mathrm{cm}^2 - \mathrm{s} - \mathrm{sr})^{-1}$ at say $\sim 10^{16.5}$ eV. These could be produced from the inverse of the process shown in Fig. 1a. The Z' would have to be produced in exceedingly dense matter in order to interact before decay. The unique possibility would seem to be the densities reached by neutron-star matter. This suggests neutron stars as discrete sources for at least some of the unusual high-energy cosmic rays. In this respect, it is worth noting that there is recent evidence [3] for anisotropy in the arrival directions for cosmic rays around 10^{18} eV, with a significant excess near the directions of the galactic center and the Cygnus region [3]. The excess flux is at the level of $\sim 10^{-18}(\text{ cm}^2 - \text{ s} - \text{ sr})^{-1}$. Among the events above 10^{19} eV, there is a curious tendency to clustering of directions [2]. One significant cluster is said [2] to encompass the direction of a known pulsar, as well as that of the Cygnus "loop". Of course, protons may be accelerated to high energies near magnetized neutron stars. [23,24].

The ideas in this paper illustrate the fact that the absence of events characterized by new dynamics at the LHC, for pp collisions at c. m. energies ~ 10 TeV, would not refute the presence of new phenomena in cosmic-ray events at $E_{\text{lab}} > 10^{16}$ eV. Evidently, the particular nature of an incident particle can be crucial, as well as the energy which it brings into the collision process. The corollary is that the cosmic-ray experiments and the coming experiments sensitive to fluxes of very high energy neutrinos (above 10^{19} eV) are essential. [25]

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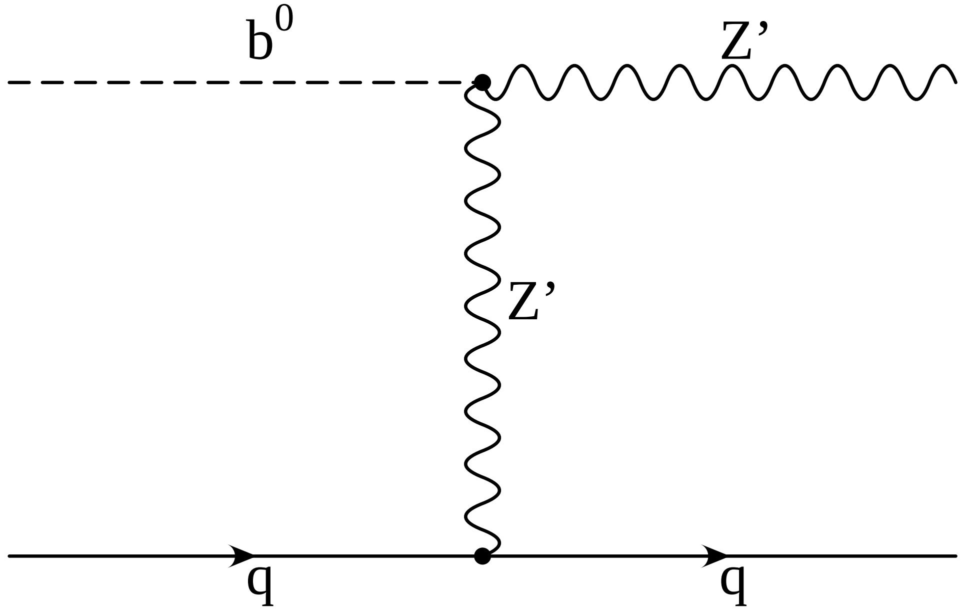

FIG. 1a. Production of a neutral massive vector boson Z' by a pseudoscalar Goldstone boson b^0 in collision with a quark q.

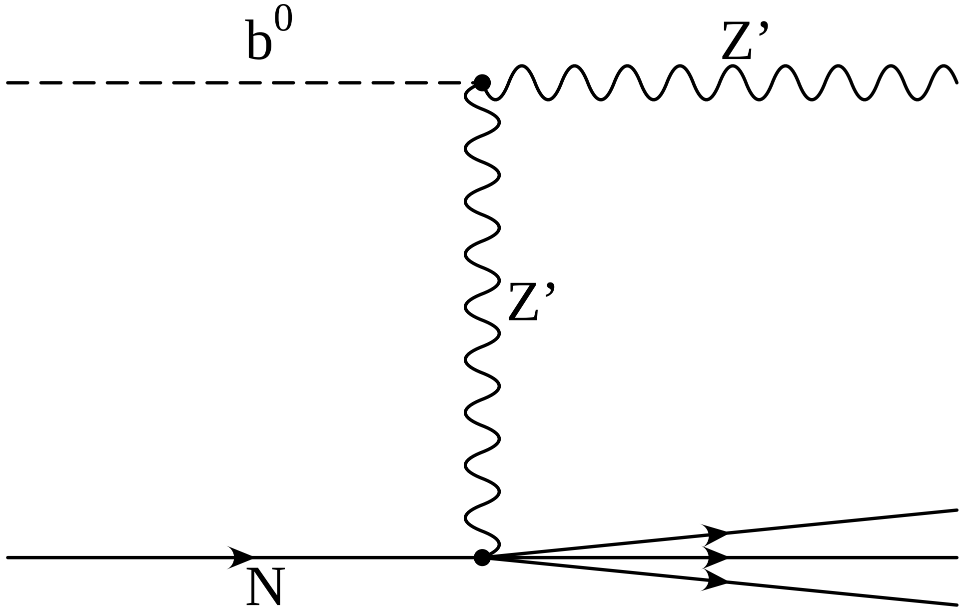

FIG. 1b. Deep-inelastic scattering initiated by b^0 in collision with a nucleon N.